

Non-locality of particle spin: a consequence of interaction energy?

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Neutron interference measurements with macroscopic beam separation allow to study the influence of magnetic fields on spin properties. By calculating the interaction energy with a dynamical and deterministic model, we are able to establish that the phase shift on one component of the neutron beam is linear with magnetic intensity, and equally, that interaction energy as well as phase shifts do not depend on the orientation of the magnetic field. The theoretical treatment allows the conclusion that the non-local properties of particle spin derive from the classical equation for interaction energy $W = -\vec{\mu} \cdot \vec{B}$ and the fact, that interaction energy does not depend on magnetic field orientation. Additionally, it can be established that the 4π symmetry of spinors in this case depends on the scaling of magnetic fields.

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Spin properties of particles, initially formalized for electron states within the hydrogen atom by Goudsmit and Uhlenbeck [1], are non-local and intrinsic features, since the mathematical description by way of Pauli matrices does not allow an identification of spin-orientation with defined directions in space [2]. As recently established, the direction of spin can be related to the polarization of intrinsic magnetic fields of particle propagation [3]. The intrinsic magnetic fields derive from the wave features of moving particles, which give rise to kinetic and electromagnetic potentials. The framework suggested was shown to be an extension of classical electrodynamics as well as quantum theory, since the treatment of micro physical systems in either case is only a limited account of intrinsic particle properties. The framework developed was applicable to electron as well as photon propagation. A treatment of EPR-type measurements [4,5] established, additionally, that a significant correlation for a pair of spin particles is likely to violate the uncertainty relations [3].

As the framework did not fully account for the non-local properties of spin, we may reconsider the problem in the context of actual measurement processes. More specifically the question, why measurements lead to the conclusion that spin *must be* a non-local property. As the most conclusive experiments on spin properties currently are neutron interference measurements with amplitude-splitting and a beam separation in macroscopic dimensions, we apply the model developed to the intrinsic qualities of neutrons. The justification for this extension of the original framework is to be seen in the fact, that the results of measurements can be accounted for in a purely classical framework of wave theory and x-ray interferences [6], which renders the fundamental equations of classical electrodynamics theoretically applica-

ble. And that the relations of classical electrodynamics, the Maxwell equations, are but a different formulation of intrinsic particle properties, has already been proved [3].

In this paper we calculate, for the first time, the dynamical and deterministic process of magnetic interactions, and it is shown that the results are in accordance with interference measurements. It will be established that non-locality of particle spin has its origins in the qualities of the interaction process. The calculation provides a reason, why interaction energy does not depend on the orientation of magnetic fields. As a final result, we will show that the 4π symmetry of spinors, which was claimed to be proved by these measurements, depends on the scaling of the magnetic field.

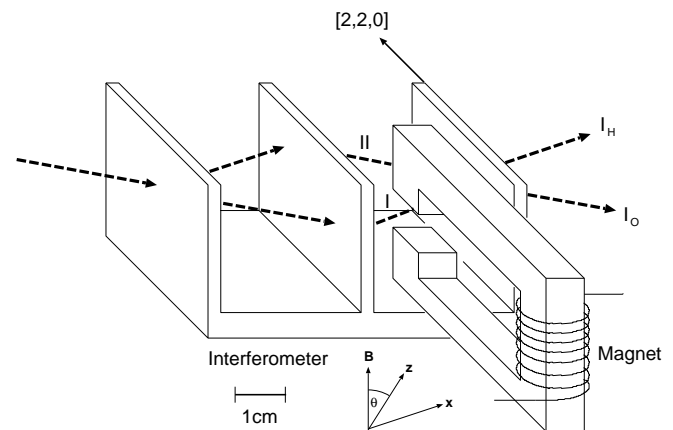


FIG. 1. Neutron interferometer for spin superposition measurement according to Rauch. The incident neutron beam is split coherently at the first plate and reflected at the middle plate. The two beam components *I* and *II* are coherently superposed at the third plate of the interferometer, a static magnetic field in the path of beam *I* leads to interference patterns depending on magnetic intensity

The neutron interference experiments were performed in the Seventies and Eighties by H. Rauch and A. Zeilinger at the Atomic Institute in Vienna [6–8]. The experimental setup consisted of a neutron source with a monochromator, the neutron beam of low amplitude was directed to an interferometer of perfect crystalline properties. The intensity of the incident neutron beam was in every case such that only a single neutron passed the interferometer at a given moment. The first plane of the interferometer served as an amplitude division device, the two separate beams (beam-separation in the range of cm) were reflected and finally recombined in the second and third plate. A static magnetic field in one path was used to alter the spin orientation of a single beam component,

and the recombination of the two separate beams then showed characteristic interference patterns depending on the intensity of the magnetic field applied. (see Fig. 1).

For our theoretical model we postulate initially that neutrons possess wave like properties described by a wave function ψ of single particles, intrinsic potentials to account for periodic mass distributions, and they shall be subject to the fundamental Planck and de Broglie relations [3]. Additionally we suppose that neutron mass in motion possesses an intrinsic magnetic field of a specific orientation ϑ , which shall be perpendicular to the axis of particle motion \vec{u} . The justification for these assumptions has to be seen, as already mentioned, in the theoretical description of interference measurements, which are compatible with classical electrodynamics and thus the intrinsic properties of particles.

The amplitude of the wave function and electromagnetic intensity are related by (I_{qt} is the intensity due to quantum theory, I_{em} the intensity obtained in classical electrodynamics) [3]:

$$\begin{aligned} I_{qt} &\propto \psi^* \psi \propto |\vec{E}|^2 \propto I_{em} \\ \Rightarrow I_{qt} &\propto I_{em} \end{aligned} \quad (1)$$

The following calculation is a *local* and *deterministic* deduction of magnetic interactions, based on intrinsic electromagnetic fields and the field equations of electromagnetic properties as well as intrinsic potentials [3]:

$$\begin{aligned} \frac{1}{u^2} \frac{\partial \vec{E}}{\partial t} &= \nabla \times \vec{B} & - \frac{\partial \vec{B}}{\partial t} &= \nabla \times \vec{E} \\ \phi_{em} &= \frac{1}{2} \left(\frac{1}{u^2} \vec{E}^2 + \vec{B}^2 \right) \end{aligned} \quad (2)$$

We consider the change of intrinsic fields due to a constant external magnetic field \vec{B}_{ext} , the field vectors shall be given by (for convenience the orientation of intrinsic magnetic fields shall denote the z-axis of our coordinate system):

$$\begin{aligned} \vec{B} &= (0, 0, B_0) \cos(k_0 x - \omega_0 t) \\ \vec{E} &= (0, E_0, 0) \cos(k_0 x - \omega_0 t) \\ \vec{B}_{ext} &= (0, -\sin \vartheta, \cos \vartheta) B_{ext} \end{aligned} \quad (3)$$

Accounting for the dynamic qualities of the process by linear increase of the magnetic field $t \in [0, \tau]$, the internal fields will be at τ :

$$\begin{aligned} E'_y &= E_0 \cos(k_0 x - \omega_0 t) - B_{ext} \frac{\cos \vartheta}{\tau} x \\ E'_z &= -B_{ext} \frac{\sin \vartheta}{\tau} x \\ B'_y &= -B_{ext} \sin \vartheta \\ B'_z &= B_0 \cos(k_0 x - \omega_0 t) + B_{ext} \cos \vartheta \end{aligned} \quad (4)$$

Additional informations about the system can be inferred from the relation between the variables x and t as well as from the relation between amplitudes [3]:

$$\frac{x}{\tau} = u_0 \quad E_0 = u_0 B_0 \quad (5)$$

The electromagnetic potential due to interaction with the magnetic field is then given by:

$$\begin{aligned} 2\phi_{em} &= [B_0 \cos(k_0 x - \omega_0 t) - B_{ext} \cos \vartheta]^2 + [B_{ext} \sin \vartheta]^2 + \\ &+ [B_0 \cos(k_0 x - \omega_0 t) + B_{ext} \cos \vartheta]^2 + [B_{ext} \sin \vartheta]^2 \end{aligned}$$

$$\phi_{em} = B_0^2 \cos^2(k_0 x - \omega_0 t) + B_{ext}^2 \quad (6)$$

The result is interesting due to two features:

- The potential of interaction does not depend on the angle ϑ of the magnetic field.

It can therefore not be formalized as the scalar product of an intrinsic magnetic moment $\vec{\mu}$ and an external field \vec{B}_{ext} :

$$W \neq -\vec{\mu} \cdot \vec{B}_{ext} \quad \vec{\mu}, \vec{B}_{ext} \in R^3 \quad (7)$$

or only, if the magnetic moment is a non-local variable: the non-local definition of particle spin in quantum theory can therefore be seen as a different expression of an equivalent result. And the motivation for this definition has to be seen in the missing account of the deterministic and dynamic development of the intrinsic variables. The result confirms a conclusion already drawn by analyzing electron photon interactions [3]: the framework of quantum theory is essentially limited to interactions, its logical implications only become obvious, if interaction processes are considered. In the context of particle spin it explains, why spin in quantum theory *cannot* be a local property: *because* interactions do not depend on the direction of field polarization.

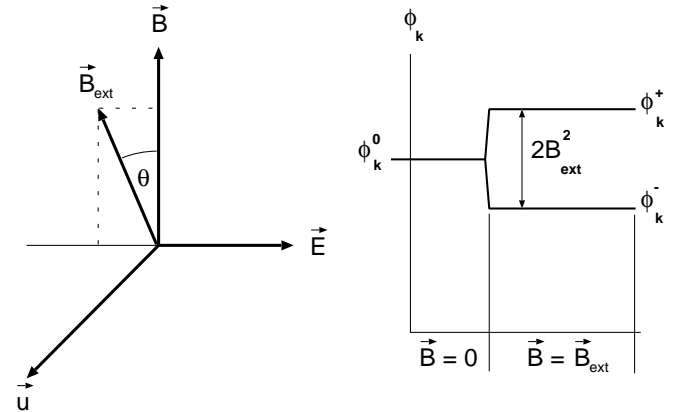


FIG. 2. Intrinsic electromagnetic fields and applied magnetostatic field of the neutron beam (left). Shift of kinetic potential due to interactions (right)

- The electromagnetic potential of the particle is higher than the original potential.

This result leaves two possibilities: either total energy density of the particle remains constant – which should

be the case for neutral particles –, or the kinetic energy density of the particle is equally altered by interactions: which should apply for charged particles. In both cases the kinetic potential during magnetic interaction is changed, the alteration can be described by:

$$\phi'_k = \phi_k^0 \pm B_{ext}^2 \quad (8)$$

Intrinsic electromagnetic fields and kinetic potentials due to external magnetic fields are displayed in Fig. 2. Due to the relations between the kinetic potential and density of mass $\phi_k = \rho u^2$ and the relation between the wave function and density of mass $\rho \propto \psi^2$ the properties of the wave function in the region of interaction will equally be changed, which means, that posterior superposition of the two separated beam parts will yield a changed interference pattern. The easiest way to calculate the changes in the affected beam is by estimating the difference of velocity. Since:

$$\langle \phi'_k - \phi_k^0 \rangle = \Delta \phi_k = -\bar{\rho} (\Delta u)^2 = -B_{ext}^2 \quad (9)$$

where $\bar{\rho}$ denotes average density of the beam, as the wave length is much shorter than the macroscopic region of the magnetic field in the interaction process, averaging is physically justified. Then the phase difference α of the beam after $t_1 = l/u_0$ seconds, where l is the linear dimension of the magnet, will be:

$$\alpha = 2\pi \frac{\Delta u \cdot t_1}{\lambda} = 2\pi \left(\frac{l}{\lambda} \cdot \frac{B_{ext}}{\sqrt{\rho} u_0^2} - n \right) \quad (10)$$

$n \in \mathbb{N}$

The theoretical result is consistent with the experimental result by Rauch, that the phase of the beam is linear with the intensity of the magnetic field applied [6]. That this phase shift is sufficient for an experimental proof of the 4π -symmetry of spinors seems to be a matter of convention, since it depends, essentially, on the scaling of the magnetic fields in terms of kinetic potentials. All that can be inferred from measurements is that magnetic fields affect the phase of the neutron beam, and equally, that this effect does not depend on the orientation of the magnetic field or the incident beam: both results are obtained in a local and deterministic manner by this calculation. Fig. 3 displays the changes of the wave function and the subsequent phase shift due to magnetic interactions.

It should be noted, that the theoretical concept is only applicable to monochromatic neutron beams. If particles have arbitrary energies then an equivalent theoretical framework also has to account for the phase shifts at different energy values: a close to classical interference pattern in this case cannot be expected.

Using the deterministic and causal model of intrinsic particle properties we have, for the first time, calculated interactions of particles in a magnetic field by evaluating the effect of external and static magnetic fields on intrinsic particle properties. The calculation was accomplished in a purely local framework, and it was established that interaction energy does not depend on the orientation of

the magnetic field. The classical description of interaction energy by way of magnetic moments was shown to be unsuitable to account for the results achieved, and it was found that the 4π symmetry of spinors depends on the scaling of magnetic intensities.

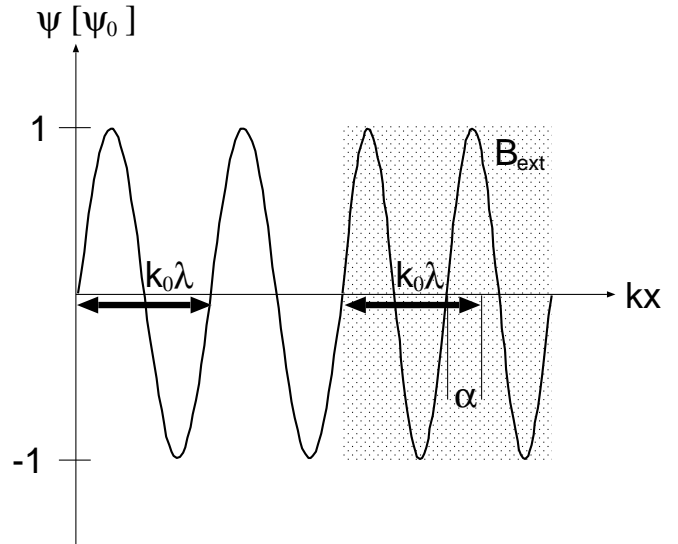


FIG. 3. Phase shift α in a magnetic field. The phase shift of the beam component I depends on the scale of the external magnetic field B_{ext}

The consequences of this new result for the framework of quantum theory seem substantial: as the theoretical calculation established, the quality of spin appears to be a simplification which does not allow for a precise treatment of interaction processes. As previous results, furthermore, revealed that the concept in itself is theoretically questionable [3], the result suggests a theoretical revision of magnetic interactions in micro physics based on deterministic and dynamical models.

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